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METHOD AND APPARATUS FOR THE DETECTION OF HYDROGENOUS MATERIALS

CROSS REFERENCES TO RELATED APPLICATIONS

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STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH AND DEVELOPMENT

This invention was made with Government support under Contract DE-AC0676RL01830 awarded by the U.S. Department of Energy. The Government has certain rights in the invention.

FIELD OF THE INVENTION

The present invention is a method and apparatus for the detection of hydrogenous materials, especially concealed hydrogenous materials, including explosives, drugs, and biological tissue. Concealment may be in the form of being buried in the ground or being otherwise hidden from view.

BACKGROUND OF THE INVENTION

Reliable detection of concealed materials such as explosives and drugs is a critical issue in providing security to both military personnel and the general population. Such detection is a first line of defense against terrorist attacks, landmines and other unexploded ordinance (UXO), and drug smuggling. Landmines and UXO kill or injure thousands each year and are a significant barrier to economic and social development in many parts of the world, seriously affecting daily life in more than 70 countries.

The metal detector, which is based on electromagnetic induction, has been used to detect land mines and UXO. Metal detectors are deficient in several aspects. In the case of UXO, metal detectors provide no differentiation between benign metallic objects and ordinance containing explosive material; that is, they are subject to false positive readings. More importantly, modern mines are encased in plastic and contain little or no metal and are often undetectable by these devices.

Ground-penetrating radar and similarly functioning microwave imaging devices detect underground targets based on the dielectric contrast. Metallic objects have very large dielectric contrast with soils and are easily seen with microwave instruments; plastic objects have smaller contrast and are less easily seen with microwave instruments. In addition, the very large change in dielectric response between the air and soil results in a large reflected signal in which the signal of the target may be hidden.

Nuclear quadrupole resonance (NQR) is also being examined for finding mines or UXO. NQR is much like nuclear magnetic resonance as used in magnetic resonance imaging systems except that it operates without the requirement for an applied magnetic field. In NQR, a radio frequency signal excites nuclei in the target and the frequency of a return signal is characteristic of the chemistry of the target. NQR is an extremely precise method for characterizing the chemical content of a nearby object. NQR signals, however, are typically very weak and subject to interference by other electromagnetic fields. The equipment for NQR is large and measurement times are long.

Prompt neutron-induced gamma-ray spectroscopy (PINS) is being actively investigated for finding mines or UXO. In PINS-like methods, neutrons are sent into the ground and induced gamma rays are examined spectroscopically for evidence of elements contained in explosives. PINS-like methods are an extremely precise method for characterizing the chemical content of a nearby object. Typical measurement times for PINS-like methods, however, are on the

order of 10 minutes, impracticably slow for an in-field application (G. Nebbia et al, "The Explodet Project: Advanced Nuclear Techniques for Humanitarian Demining," 6th International Conference on Applications of Neutron Science, June 1999, Crete and P. C. Womble et al, " Landmine Identification Using Pulsed Fast -Thermal Neutron Analysis," 6th International Conference on Applications of Neutron Science, June 1999, Crete).

An important feature in common for most explosives and drug contraband is that these materials contain hydrogen and consequently are able to be detected with another neutron technique of neutron scattering. For example, neutron scattering has been used to detect plastic mines (F. D. Brooks and A. Buffler, "Detection of Plastic Land Mines by Neutron Backscattering," 6th International Conference on Applications of Neutron Science, June 1999, Crete). In this approach, a fast neutron source and thermal neutron sensor in close proximity were used. The presence of a mine was indicated by thermal neutron signals caused by scattering and moderation of fast neutrons in the presence of hydrogen. This approach, however, has an inferior signal-to-noise ratio because fast neutrons emitted by the source or backscattered directly from the soil, although poorly detected by the thermal neutron sensor, greatly outnumber the thermal neutron signals. Thus, although this concept is amenable to incorporation in a small, lightweight instrument, the background noise is relatively large so detection efficacy is poor.

Similarly, attempts to image buried hydrogenous material (e.g., a simulated plastic land mine) using neutron scattering techniques have been made using coded-aperture techniques and high-spatial precision, pressurized He-3 detectors. Because the background noise, associated with detection of fast neutrons, is appreciable, the image quality is less than satisfactory (Peter Vanier and Leon Forman, "Advances in Imaging With Thermal Neutrons", Proceedings of the Institute of Nuclear Materials Management, 37th Annual Meeting, Naples, FL, July 1966). An alternative approach to imaging is provided by Peurrung et

al. (A. J. Peurrung, P. L. Reeder, E. A. Lepel, and D. C. Stromswold, "Location of neutron sources using moderator-free directional thermal neutron detectors", IEEE Transactions on Nuclear Science, Vol 44, number 3, part 1, pp 563-7, July 1997). In this approach, a large aspect-ratio collimator in front of a position-sensitive neutron detector was used. Again, however, the background noise associated with detection of fast neutrons degrades the quality of the image.

Accordingly, there is a continuing need for a low-noise and sensitive device for detecting objects containing hydrogenous material.

BRIEF SUMMARY OF THE INVENTION

The present invention is an improved method and apparatus that employs both neutron scattering and time-tagged neutron techniques to address such types of needs. Time-tagged neutron techniques have been used in a number of applications in the past for identification of nuclear weapons or nuclear materials (T. Uckan et al, "^{252}Cf-source-correlated transmission measurements for uranyl fluoride deposit in a 24-in-OD process pipe," Nuclear Instruments and Methods in Physics Research, 1999, 26-34). Time-tagged neutron systems make a gating or timing signal available to neutron sensor(s) based on the point in time at which a neutron leaves the source. In these nuclear applications, the time-tagged neutron source is used as a marker to measure response of a target to neutrons and gamma-rays. The fast (nanosecond-scale) time-correlated time-of-flight gamma-ray and neutron transmissions through, and reactions with, the target provide a means for distinguishing between various fissile material assemblies. Such time-tagged sources are commonly fabricated by incorporating a neutron source, such as ^{252}Cf, into a fission chamber.

Another source for time-tagged neutrons is a neutron generator, which is commonly constructed by accelerating deuterium nuclei and reacting these with either other deuterium nuclei or tritium nuclei. Such generators can be operated either in the pulsed or continuous mode. In the pulsed mode, these provide a

time-correlated source of neutrons. Portable neutron generators are commonly available with outputs of up to 10^6 n/pulse but can be operated at smaller outputs.

The present invention detects hydrogenous materials by measuring the backscattering of neutrons emitted from a neutron source that have been slowed to thermal regime velocities (thermalized) by their interaction with hydrogen atoms in the targeted environment. The sensitivity of the detector has been greatly enhanced by utilizing time-tagged neutrons and a timing circuit in the control system. This timing circuit prevents the counting or detection of unwanted "prompt" neutrons (e.g., by disabling the neutron sensor) during a first time interval after the emission of the neutrons from the neutron source is detected and allows detection of neutrons thereafter (this first time interval is hereinafter referred to simply as "time delay"). The sensitivity of the detector may be further enhanced by having the timing circuit allow the counting or detection of neutrons during a second time interval that follows the time delay and prevent the counting or detection of neutrons after this second time interval (this second time interval is hereinafter referred to simply as "window"). Utilization of such a window prevents the detection of neutrons that have been moderated by hydrogen far from the detector (e.g., moisture in surrounding soil) and thus, reduces noise.

The detector of the present invention, therefore, does not register any neutrons that return to the neutron sensor during the time delay. Most neutrons returning during this time (i.e., "prompt neutrons") are fast neutrons that were not scattered from hydrogenous materials and produce unwanted background noise. The detector may further not register any neutrons that return to the neutron sensor after an employed window. Most neutrons returning after the window (i.e., "late neutrons") are slow neutrons that have been thermalized far from the neutron sensor and migrate in to produce additional unwanted background noise. This effect is most pronounced when the hydrogen content far from the sensor

(e.g., moisture in the surrounding soil) is greatest.

Further improvement in the signal-to-noise ratio is achieved when the neutron sensor in the detector comprises a gas-proportional counter tube and applying pulse-height discrimination to the detected neutron signal. Discriminating against small signals is standard practice for reducing electronic noise; using an upper-level discriminator to discriminate against large signals, however, provides discrimination against fast neutrons coming directly from the neutron source in the detector or arising from backscatter.

The detector of the present invention may be moved or scanned over a targeted area such as soil or ground. The detector may be operated in a count mode, image mode, or combination thereof. In the count mode, an increase in detection rates of thermalized neutrons by the detector indicates the presence of hydrogenous material. Alternatively, in the image mode, a visual spacial representation of any increased detection rate of thermalized neutrons is provided to the user.

Imaging for the detection of hydrogenous material is based on the assumption that the last scattering position of a near-thermal neutron is at, or near, the hydrogenous material. This assumption is physically reasonable--the mean path between collisions for a slow neutron (less than 500 times as fast as a fully thermalized neutron) in RDX (a commonly-used explosive) for instance, is a little less than 0.8 cm; in dry sand it is about 4 cm. Thus, the slow neutrons will most likely appear to emanate from the target.

There are several approaches to spatially resolving the neutron count signal, or in another words, providing the spatial location of the target. The simplest approach is a modification of a quasi-imaging approach that has been used in astronomy for determining the locations of x-ray and gamma-ray sources and adapted for neutrons by Peurrung et al; this is simply a large-open-area collimator that restricts the angle at which neutrons can enter the detector. Peurrung et al have shown that a honeycomb structure can perform this function

quite well. The collimator should be constructed of a material that absorbs slow neutrons well and slows neutrons poorly.

In this approach, the thermal neutron detector also needs to have the ability to report the position at which the neutron is detected. The collimator limits the direction from which the slow neutrons may be coming; a position-sensitive detector will provide source-shape information. ^{3}He tubes inherently have a position-sensitivity capability in one dimension with a resolution equal to approximately their diameter; resistive-wire tubes can provide this kind of information in two dimensions. If greater precision is desired, the neutron detection can be done with crossed scintillating fibers, which could provide sub-millimeter resolution. This quasi-imaging approach will reduce the effect of inhomogeneities in moisture content and will reduce the halo or penumbra effect in which a target off the axis of the detector affects the count rate of the detector. By reducing the effect of off-axis neutrons, the signal-to-noise ratio will also improve. Because signal neutrons are also being attenuated, more measurement time, to provide adequate signal per pixel, may be required.

True imaging, in which off-axis neutrons as well as near-axis neutrons contribute to the image, can be achieved by forming a pinhole camera, or its modern equivalent, a coded-aperture camera using the techniques of Vanier and Forman. A coded-aperture camera is a many-pinhole pinhole camera in which the image is reconstructed computationally. The open area of a coded-aperture camera can be 50% of the front surface; potentially the utilization of the slow backscattered neutrons can be much greater than that that for a simple collimated system. This approach requires much greater complexity for the physical and electronic parts of the system.

In yet another implementation, if the imaging capability is included, the detector may be moved or scanned over a targeted area in a nonimaging counting mode, and, when a suspicious area is found, converted to imaging mode to provide an image of the objects generating the signal. This operational

mode provides for rapid scanning and slower but high-confidence confirmation of the target.

The present invention has substantial advantages over prior methods for the detection and imaging of concealed explosives, drugs and other hydrogenous materials including biological tissue in relatively inorganic environments. The time-tagged neutron source, together with judicious selection of the time delay, the size of any window, and any lower and upper discriminator levels, greatly increases the signal-to-noise ratio making the sensitivity for detecting hydrogenous materials greater than previous detectors. The detector is rugged and lightweight (man-portable) and provides a fast response time compared to other methods.

An object of the present invention is to improve the detection sensitivity, and image quality, of concealed hydrogenous materials, including explosives and drugs.

A further object of the present invention is to improve the ability to detect low- or non-metal land mines.

A further object of the present invention is to improve the ability to detect contraband.

A further object of the present invention is to improve the ability to detect human or animal remains.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1a is a cross-sectional side view of a schematic representation of an embodiment of the present invention whereby the detector is handheld;

FIG. 1b is a cross-sectional side view of a schematic representation of another embodiment of the present invention whereby the detector is mounted on a vehicle;

FIG 2a is a cross-sectional side view of a schematic representation of a collimated sensing head that may be used in an imaging mode;

FIG 2b is a bottom view of the collimated sensing head shown in **FIG. 2a**;

FIG 3a is a cross-sectional side view of a schematic representation of a coded-aperture sensing head that may be used in an imaging mode;

FIG 3b is a bottom view of the coded-aperture sensing head shown in **FIG. 3a**;

FIG. 4a is a cross-sectional side view of an experimental setup for testing time delays of the present invention;

FIG. 4b is a magnified view of the sensing head used in the experimental setup of **FIG. 4a**;

FIG. 4c is a schematic representation of the electronic circuitry used in the experimental setup of **FIG. 4a**;

FIG. 5a is a cross-sectional side view of an experimental setup for testing time delays and pulse-height discrimination of the present invention;

FIG. 5b is a magnified view of the sensing head used in the experimental setup of **FIG. 5a**;

FIG. 5c is a schematic representation of the electronic circuitry used in the experimental set up of **FIG. 5a**;

FIG. 6a is a chart showing a pulse-height spectrum obtained from the testing using the experimental setup of **FIG. 5a**;

FIG. 6b is a chart showing the detection efficiency as a function of lower-level discriminator with no upper-level discriminator for 100-s count obtained from testing using the experimental setup of **FIG. 5a**;

FIG. 6c is a chart showing the detection efficiency as a function of upper-level discriminator with lower-level discriminator at channel 39 for 100-s count obtained from testing using the experimental setup of **FIG. 5a**;

FIG. 7a provides a cross-sectional side view of the physical model used in the computer model;

FIG. 7b is a magnified view of a section of the computer model of **FIG. 7a**;

FIG. 7c is a chart showing the detection efficiency as a function of the time delay using the computer model of **FIG. 7a**;

FIG. 7d is a chart showing the improvement of detection efficiency as a function of the time delay using the computer model of **FIG. 7a**;

FIG. 7e is a chart showing the detection efficiency as a function of the time delay using the computer model of **FIG. 7a** with the target 1 cm deep;

FIG. 7f is a chart showing the improvement of detection efficiency as a function of the time delay using the computer model of **FIG. 7a** with the target 1 cm deep;

FIG. 7g is a chart showing the detection efficiency as a function of the time delay using the computer model of **FIG. 7a** with the target 2.5 cm deep;

FIG. 7h is a chart showing the improvement of detection efficiency as a function of the time delay using the computer model of **FIG. 7a** with the target 2.5 cm deep;

FIG. 7i is a chart showing the detection efficiency as a function of window size using the computer model of **FIG. 7a** with the target 1 cm deep;

FIG. 7j is a chart showing the improvement of detection efficiency as a function of window size using the computer model of **FIG. 7a** with the target 1 cm deep;

FIG. 7k is a chart showing the detection efficiency as a function of window size using the computer model of **FIG. 7a** with the target 2.5 cm deep;

FIG. 7l is a chart showing the improvement of detection efficiency as a function of window size using the computer model of **FIG. 7a** with the target 2.5 cm deep;

FIG. 7m is a chart showing the detection efficiency as a function of window size using the computer model of **FIG. 7a** with dry soil; and

FIG. 7n is a chart showing the improvement of detection efficiency as a function of window size using the computer model of **FIG. 7a** with dry soil.

DETAILED DESCRIPTION OF THE INVENTION

The present invention is a method and apparatus for detecting hydrogenous materials, especially materials concealed in relatively inorganic environments, by measuring the backscattering of neutrons that have been thermalized by their interaction with hydrogen atoms. In one embodiment of the present invention, shown schematically in **FIG. 1a**, the detector **10** is a handheld device. The detector **10** has at least one sensing head **20**, which may be a simple counting device, a device for imaging, or one performing both functionalities. The sensing head **20** comprises a neutron sensor **60** (hereinafter referred to simply as "sensor") and a neutron shield **70**. As shown in the embodiment of **FIG. 1a**, a time-tagged neutron source **50** (hereinafter referred to simply as "source") may be physically colocated with the sensing head **20**, though the present invention is not limited to such configurations. For example, the source **50** may be physically separated from the sensing head **20** to provide a stream of neutrons toward a suspected hydrogenous material that are subsequently backscattered from the material to the sensing head **20**. The detector **10** further comprises a control system **30** that may be physically connected to the sensing head **20** and source **50** by way of an extension arm **40**. The control system **30** comprises a user interface **80** and electronic circuitry **90**. The electronic circuitry for the sensing head **20**, source **50**, and user interface **80** includes the necessary power supplies, amplifiers, timing circuit, and other electrical components. The user interface **80** provides the means for communicating the measurement results to the user. The signal from the sensor **60**, dependent on the amount of hydrogenous material detected, is sent to the user interface **80** by way of the electronic circuitry **90**. The user interface **80** may include, but is not limited to, an audible enunciator (e.g., alarm, variable-sounding

horn), an analog or digital meter or display, a mechanical vibrator, and combinations thereof.

In one embodiment, the electronic circuitry **90** disables the sensor **60** during a time delay after the emission of a neutron from the source **50** is detected and enables the sensor **60** thereafter. In another embodiment, the electronic circuitry **90** disables the sensor **60** during a time delay after the emission of a neutron from the source **50** is detected, then enables the sensor **60** during a window, and then disables the sensor **60** thereafter. The extension arm **40** physically supports the sensing head **20** and control system **30** while providing an electrical conduit between these two components. The sensing head **20** may be moved over the ground **100** to scan an area proximate a suspected target **110**. An increase in detection rates of thermalized neutrons by the sensor **60** indicates the presence of hydrogenous materials. In the imaging mode, a region causing increased scattering of detected neutrons indicates a greater than ambient concentration of hydrogen.

An alternative embodiment of the present invention is shown schematically in **FIG. 1b** whereby the detector **10** comprises a scanning vehicle **120** and, as above, has at least one sensing head **20** and a control system **30**. Multiple sensing heads **20** may be arranged and mounted directly on the scanning vehicle **120** or arranged and mounted on one or more extension arms **40** to form an array for efficient scanning. A variation of this embodiment is whereby the sensing head **20** comprises one or more sources **50** with one or more sensors **60** and a neutron shield **70**. Such a detector would be suitable where large areas need to be scanned and/or remote operation was required. If remote operation is required, the user interface **80** may comprise a wireless transmitter that communicates the presence of a hydrogenous material to a user at a remote receiving station.

The present invention is not limited to the embodiments specifically shown in **FIGs. 1a-b** and is not limited to applications that require scanning of the

ground **100**. For example, the target **110** may be hidden from view in buildings, vehicles, baggage, or other structures. Furthermore, as is known to those skilled in the art, the specific locations for the electronic circuitry **90** and user interface **80** may be different and quite variable depending on specific user requirements and detector applications. Yet further, the extension arm **40** may or may not be required and may be designed using a variety of geometries.

In both embodiments of **FIGs. 1a-b**, neutrons emitted from the source **50** have a variety of fates. Some neutrons will go directly from the source **50** to the sensor **60** and either pass through the sensor **60** or react within the sensor **60**, giving a detection signal. Because the majority of emitted neutrons are fast, these events will occur very quickly after emission. Some neutrons will collide with heavy nuclei in the ground **100** and, after one or more collisions, pass back to the sensor **60**. Because these collisions are with heavy nuclei, compared to the hydrogen nuclei, the neutron loses little of its speed so that detection events with these interactions will occur quickly after emission. A few of the neutrons will collide with a hydrogen nucleus, either in an initial collision or subsequent to a collision with a heavier nucleus. Such neutrons will be slowed substantially; those that make several collisions with hydrogen nuclei will be slowed sufficiently that they have a high probability of detection in the sensor **60**. Because the hydrogen slows the neutron substantially, detection events for these will occur considerably later after emission than events from neutrons passing directly to the sensor **60** or after collision with the ground **100**, which have not been slowed.

Thus, if only those detection events that occur after the judiciously selected time delay are counted, the relative efficiency of detection of neutrons that have interacted with hydrogen, compared to those that have not interacted with hydrogen, is improved. This preferential detection of thermalized neutrons, after the time expected for their interaction and return from hydrogen nuclei located in the immediate vicinity of the source and detector, results in an improved ability to rapidly distinguish concentrations of hydrogenous materials

such as organic explosives.

The source **50** may be any of the following:

(1) a fission source that provides a distinct electronic signal for each fission event resulting in the emission of a neutron, such as ^{252}Cf or other spontaneously fissioning nucleus in a fission chamber, or

(2) a fission source that provides a distinct electronic signal for each fission event resulting in the emission of a neutron and discriminating against other decay modes, such as ^{252}Cf or other spontaneously fissioning nucleus together with a scintillator, sensing the multitude of gamma rays emitted simultaneously with the neutron during the fission event, or

(3) a neutron generator, operated in pulse mode, such as the Model A-801 sold by MF Physics of Colorado Springs, CO , in which ions are accelerated onto a target, the product of which is neutrons, or

(4) an (alpha, n) source, contained within a cross-luminescing scintillator system such that each (alpha, n) reaction produces an electronic signal distinguished from alpha particle scintillations that produce no neutrons, or

(5) a pulsed (gamma, n) source or (x-ray, n) source, producing prompt photoneutrons from a target such as beryllium.

Thermal-neutron sensors operate on the basis of a nuclear reaction in which the neutron is absorbed by a nucleus, such as ^{6}Li, ^{10}B, or ^{3}He. In such reactions an energetic and massive particle, often an alpha particle or a tritium (^{3}H) nucleus, is emitted. The energy associated with the reaction provides a means for detection of the reaction. These reactions have greater probability of occurrence for thermal neutrons than for fast. The reaction probability varies approximately inversely with the velocity of the neutron. This means that fast neutrons have a possibility, albeit small, for engaging in the detection reaction. However, the much greater number of fast neutrons means that these contribute to the count rate of the detector.

The sensor **60** should be a detector whereby the efficiency and sensitivity

is greater for slower neutrons compared to faster neutrons, for example any of the following:

(1) a ^{3}He gas-proportional counter, or

(2) a $^{10}BF_3$ gas-proportional counter, or

(3) a ^{6}Li containing scintillating glass or scintillating glass fiber, or

(4) a ^{6}Li or ^{10}B containing scintillating plastic or scintillating plastic fiber, or

(5) a ^{6}Li or ^{10}B containing scintillating crystal, or

(6) any combination of the foregoing.

In an imaging implementation, the sensor **60** should have the ability to determine the position at which the neutron was detected. This may be achieved, for example, by using a multi-wire, ^{3}He or $^{10}BF_3$ gas-proportional counter, by using an array of resistive-wire, ^{3}He or $^{10}BF_3$ gas-proportional counters, by using an array of neutron-sensitive, scintillating glass or scintillating plastic fiber, connected to photomultiplier tubes in such a way that the position of the neutron interaction is detected and reported, or some combination of the above.

The neutron shield **70** should be an efficient absorber of thermal neutrons, for example, any of the following:

(1) a ^{10}B-containing material, or

(2) a ^{6}Li-containing material, or

(3) a Cd-containing material, or

(4) a Gd-containing material, or

(5) any combination of the foregoing.

All other things being equal, neutron shield **70** materials such as (1) or (2) above are preferable because these also serve to provide some shielding for faster neutrons. Furthermore, it is preferred that the neutron shield **70** be fabricated of non-hydrogenous material because any hydrogen in the vicinity of the source **50** or sensor **60** will serve to increase the noise associated with fast

neutrons moderated by the neutron shield **70** versus the targeted hydrogenous material.

Imaging may be performed on the basis of using a sensing head **20'** comprising a collimating material **72** as shown in **FIGs. 2a-b** or a sensing head **20''** comprising a coded-array aperture **74** as shown in **FIGs. 3a-b**. The collimating material **72** or the material forming the basis of the coded-array aperture **74** should be an efficient absorber of thermal neutrons, for example, any of the following:

(1) a ^{10}B-containing material, or

(2) a ^{6}Li-containing material, or

(3) a Cd-containing material, or

(4) a Gd-containing material, or

(5) any combination of the foregoing.

All things being equal, the collimating material **72** such as (1) or (2) are preferred because these also serve to provide some shielding for faster neutrons. Material such as (3) or (4) material are prefered for the basis of the coded-array aperture **74** because these are less likely to erroneously encode information about the source position of a fast neutron.

EXAMPLE 1

An experimental setup for demonstrating the effect of using a time delay of the present invention is shown in **FIGs. 4a-b**. The electronic circuitry **90'** used for this experimental setup is shown in **FIG. 4c**. The present invention is not limited to the specific design of electronic circuitry **90'** of **FIG. 4c** since it is apparent to those skilled in the art of electronic circuits that alternative circuitry and components could be used to provide the necessary power, controls, and time delay. In this setup, the source **50** was a ^{252}Cf fission source fabricated for Oak Ridge National Laboratory with a Model Q6456-1 preamplifier **200** made by RIS Corporation. High voltage for the source **50** was provided by an Ortec Model

556 power supply **205** at +400 V (high voltage for the source **50** was supplied through the Q6456-1 preamplifier **200**). Power for the preamplifier **200** was supplied by a Tektronics PS280 power supply operating at +15V (not shown).

It is preferred that the sensor **60** is resistant to gamma-ray radiation, because it will be operating in a gamma-ray environment. In this setup, the sensor **60** comprised a ^{3}He gas-proportional counter consisting of six, 0.4053 megaPascal, 2.54-cm diameter, Reuter-Stokes (RS-P4-0814-207) tubes **210** with 36 cm of active length held between two aluminum plates **215**. A model 142PC preamplifier **220** fabricated by Ortec was used with the sensor **60**. High voltage for the ^{3}He gas-proportional counter was provided by an Ortec Model 456 power supply **225** operating at +1100V (high voltage for the ^{3}He tubes was supplied through the 142 PC preamplifier **220**).

The neutron shield **70** was made from sheets of metallic Cd and had a total thickness of approximately 0.1 cm. It is preferred that the neutron shield **70** is made of boron, lithium, or combinations thereof because these materials attenuate neutrons over all energy ranges.

As shown in **FIG. 4c**, the signal from the ^{3}He gas-proportional counter preamplifier **220** was sent to an Ortec 571 amplifier **230** and thence to an EG&G CF8000 constant-fraction discriminator **235**; those pulses more negative than – 0.120 V were sent to two Ortec 772 counters **240** slaved to an Ortec 773 counter/timer **245**.

The signal from the source preamplifier **200** was sent to another bay of the EG&G CF8000 constant-fraction discriminator **250**; those pulses more negative than -0.108 V, which was found to include essentially all fission events, were sent to an Ortec 416A gate and delay generator **255**; the positive signal from this unit was sent to a BNC 7010 digital delay (not shown because multiple delays were only required to examine the effects of variation in delay), thence to a signal complement generator (fabricated in-house, also not shown because it was only required to invert the gate), to an Ortec 427A delay **260**, for conditioning, and

finally to the gate of one of the Ortec 772 counters **240**.

Various time delays are possible; 5 microseconds was found to be best in this experiment. The time delay efficacy maximum was found to be broad so other time delays would provide only minor degradation of efficacy. In other experiments, slightly shorter delays were used with no apparent degradation of performance.

The experimental setup provided two signals: a count (for a period determined by the timer) of the total number of neutrons detected ("ungated") and the total number of neutrons detected after a time delay ("gated"). For the preferred embodiment, electronic circuitry **90'** providing substantially similar functions to those in this experiment would be used, except that there is no need for the ungated signal, because the ungated signal was only used as a diagnostic comparison for the efficacy of the time-tagged approach.

The experimental setup of **FIGs. 4a-c** consisted of a series of 100-sec counts with the sensing head **20'''** near the surface of ground **100** simulated using silica sand bed. The experiment consisted of placing the sensing head **20'''** above the surface of the ground **100** with no target **110** present and with a target **110** located at various depths (top surface of the target **110** to the ground **100** surface) ranging from approximately -2.54 cm (lying on the surface) to buried 17.78 cm beneath the surface. Targets included:

- a 300-gram polyethylene disk
- a 86.5-g simulated land mine
- a 215-g simulated land mine
- a 499-g simulated land mine

The simulated mines were fabricated for the U. S. PM - Mines, Countermine and Demolitions (PM-MCD) at Fort Belvoir, VA by VSE Corporation of Alexandria, VA to provide a consistent basis for comparing detection technologies.

With the detection signal defined as the difference in number of counts between when a target is present and when it is absent, compared to the

expected variance when the target is absent (this detection signal is expressed as n-sigma), time-tagging with a time delay consistently provided an improvement of approximately a factor of 1.9, that is, the detection signal was approximately 1.9 times as great when time-tagging with a time delay was used than when it was not used. For example, when the 300-g polyethylene disk was used, the results listed in Table 1 were obtained. Table 1 shows that the ratio of counts when the target was present to that when it was absent was substantially greater (improved) when time-tagging with a time delay was used. This affirms the value of the method for detection of hydrogenous material. The results of Table 1, interpreted in terms of detection efficiency using a statistical measure, are shown in Table 2.

Table 1. Counts/Second

(counts per 100-sec interval divided by 100,detector 1.9 cm above silica sand)

Depth (cm)	Counts ungated	Counts gated	Ratio of signal with target to without (ungated)	Ratio of signal with target to without (gated)
no target	71.58	12.44	n.a.	n.a.
0	1134.29	824.42	15.85	66.27
2.54	639.47	454.43	8.93	36.53
5.08	411.55	279.79	5.75	22.49
7.62	295.01	189.66	4.12	15.25
10.16	196.62	111.80	2.75	8.99
17.78	110.83	41.87	1.55	3.37

Table 2. Detection Efficiency

(number of sigma greater than noise, detector 1.9 cm above silica sand)

Depth (cm)	Ungated	Gated	Gated/Ungated Ratio
0	125.6	230.2	1.8
2.54	67.1	125.3	1.9
5.08	40.2	75.8	1.9
7.62	26.4	50.3	1.9
10.16	14.8	28.2	1.9
17.78	4.6	8.3	1.8

The gated/ungated ratio of approximately 1.9 in detection efficiency is extremely significant. For instance, a 1-sigma detection means that there is approximately a 68% probability that the signal is caused by a target rather than a statistical variation; at 1.9-sigma there is nearly a 95% probability that the signal is caused by a target. The data in Table 2 provide a quantitative description of the efficacy of the use of time-tagging with a time delay.

EXAMPLE 2

An experimental setup for demonstrating the efficacy of the present invention with pulse-height discrimination is shown in **FIGs. 5a-b**. Although this example demonstrates that pulse-height discrimination alone improves the signal-to-noise ratio, and, therefore, the detection efficacy, it further demonstrates that use of pulse-height discrimination in conjunction with a time delay provides greater improvement in signal-to-noise ratio than either taken separately. The electronic circuitry **90"** used for this experimental setup is shown in **FIG. 5c**. The present invention is again not limited to the electronic circuitry **90"** of **FIG. 5c** since it is apparent to those skilled in the art of electronic

circuits that alternative circuitry and components could be used to provide the necessary power, controls, and timing circuit.

The source **50** was a ^{252}Cf fission source fabricated for Oak Ridge National Laboratory with an Model 10A, amplifier discriminator, **300,** manufactured by Precision Data Technology. . High voltage for the source **50** was provided by an Ortec Model 556 power supply **205** at +400 V (high voltage for the source **50** was supplied through the amplifier discriminator **300**). Power for the amplifier discriminator **300** was taken from the high-voltage supply **205**. Signals from the source **50** were sent to an Ortec Model 416 Gate/Delay generator **310** which provided a 5-microsecond pulse.

The sensor **60'** comprised a ^{3}He gas-proportional counter consisting of six, 0.4053 megaPascal, 2.54-cm diameter, Reuter-Stokes (RS-P4-0814-207) tubes **210** with 36 cm of active length mounted in an aluminum box **320**. The source **50** was mounted between the tubes with three tubes on each side. A model 142PC preamplifier **220** fabricated by Ortec was used with the sensor **60'**. High voltage for the ^{3}He gas-proportional counter was provided by an Ortec Model 456 power supply **225** operating at +1100V (high voltage for the ^{3}He tubes was supplied through the 142 PC preamplifier **220**).

For this experiment, the neutron shield **70'** was made from sheets of metallic Gd and had a total thickness of approximately 0.01 cm. It is preferred, however, that the neutron shield **70'** is made of boron, lithium, or combinations thereof because these materials attenuate neutrons over all energy ranges.

As shown in **FIG. 5c**, the signal from the ^{3}He gas-proportional counter preamplifier **220** was sent to an Ortec 571 amplifier **230**, operating with a shaping time of 2 microseconds, and thence to a Nomad pulse-height analyzer **320**; the 5-microsecond pulse from the gate/delay generator **310** was fed to the pulse-height analyzer **320** for coincidence counting.

When a neutron interacts with ^{3}He in a gas-proportional counter, it creates a ^{4}He compound nucleus in an excited state which decays to a ^{3}H nucleus with

the emission of a proton. The proton creates ion pairs (electrons and positively charged ions) that are collected on the cathode and anode. The number of ion pairs collected, which determines the proportional counter pulse height, is directly related to the energy of the proton and ^3H nucleus. In turn, this energy is equal to the sum of the reaction energy, 0.764 MeV, and the kinetic energy of the incoming neutron. Thus, the pulse-height spectrum, contains a limited amount of information about the energy spectrum of the incident neutron.

The pulse-height analyzer **320** separated the pulses, by pulse height, into height bins (channels) although not all channels reported data (the maximum channel was set to be well above the pulse-height region of interest so as to be certain to capture all the significant data. The lower-level discriminator setting on the pulse-height analyzer **320** was set sufficiently low such that noise signals below neutron-detection signals were included. Data from the pulse-height analyzer **320** was sent to a portable computer for logging (not shown).

The experimental setup was operated, for testing purposes, in two modes: a count (for a live-time period determined by the pulse-height analyzer **320**) of the total number of neutrons detected ("ungated") and the total number of neutrons detected during the period of the 5 microsecond pulse ("coincidence"). Data for the anticoincidence mode ("gated") was derived by channel-wise subtraction of the coincidence data from the ungated data.

The testing using the experimental setup of **FIGs. 5a-c** consisted of a series of 100-sec pulse-height spectra counts (**FIG. 6a**) with the sensing head **20""** near the surface of the ground **100** simulated using a silica sand bed. The experiment consisted of placing the sensing head **20""** above the surface (4.44 cm) of the ground **100** with no target **110** present and with a target **110** located flush with the surface. Targets included:

- a 215-g simulated land mine
- a 499-g simulated land mine

The simulated mines were fabricated for the U. S. PM - Mines, Countermine and

Demolitions (PM-MCD) at Fort Belvoir, VA by VSE Corporation of Alexandria, VA to provide a consistent basis for comparing detection technologies.

Two analysis techniques were adopted, respectively, to test the effect of a lower-level discriminator setting and an upper-level discriminator setting. To test the effect of the lower-level discriminator setting, a cumulative total of the number of counts, with and without mine simulant targets, was calculated starting at the highest channel. The detection signal, defined as the difference in number of counts between when a target is present and when it is absent, compared to the expected variance when the target is absent (this detection signal is expressed as n-sigma), for this set of experimental conditions, showed (**FIG. 6b**) a distinct maximum at or near channel 39 for both time-tagged cases and cases in which time tagging is not used. This simply means that data below about channel 39 add more noise than signal and should not be used. This provides guidance that the lower-level discriminator setting, for this set of experimental conditions, should be set at or near channel 39 for maximum detection sensitivity.

To test the effect of the upper-level discriminator setting, a cumulative total of the number of counts, with and without mine simulant targets, was calculated starting at channel 39. The detection signal, defined as the difference in number of counts between when a target is present and when it is absent, compared to the expected variance when the target is absent (this detection signal is expressed as n-sigma), for this set of experimental conditions, showed a distinct maximum at or near channel 160 for both time-tagged cases and cases in which time tagging is not used. For these experimental conditions, this maximum ranged from greater than 7% to greater than 12% more than the asymptotic value. This means that data above about channel 160 (**FIG. 6c**) add more noise than signal and should not be used. These data above about channel 160 contain more pulses arising from the interaction of more-energetic neutrons with the He-3 so this upper-level discrimination aids in discrimination against neutrons that have not interacted with hydrogen. This provides guidance that the upper-

level discriminator setting, for this set of experimental conditions, should be set at or near channel 160 for maximum detection sensitivity.

EXAMPLE 3

A series of computer experiments specifically for testing the efficacy of a window in the present invention, but also providing information about the optimal time delay, if used in a time delay-only mode, were performed using a computer model of the present invention. MCNP (Monte Carlo N-Particle Transport Code System), version 4a, was used for modeling the behavior of neutrons in interaction with matter. The physics of neutron interactions is well understood and appropriately included in this code; to the extent that the essentials of the computer experiment are incorporated in the input to the code, MCNP will give statistically meaningful results. If a sufficient number of neutron histories are examined, the computer model answers will accurately predict the results of an actual physical experiment. In reality, MCNP results can be better tests of the pertinent physics than those for a physical experiment because, in all physical experimental arrangements, controlling stray neutrons is very difficult. Additionally, computer experiments can be free of the constraints imposed by a particular set of electronics and can assist in focusing on electronic improvements. The concept of using a window for further neutron discrimination was based on discovering, during laboratory and field experiments, that soil greater than 1 meter from the source affected the neutron measurements and the resulting hypothesis that, although the mass of soil moisture distant from the source can be very great, its influence can be reduced by cutting off measurements for times such that thermal neutrons traveling more than a few 10s of cm are not counted. That is, these experiments showed that the optimal time delay depends on soil conditions and, in addition, when hydrogen content, in particular soil moisture, increases, the use of a window would likely improve the signal-to-noise ratio. The use of a window would reduce the effect of soil

hydrogen at a great distance from the source and sensor.

The computer model used in the series of computer experiments, shown in **FIGs. 7a-b**, consisted of a 10-meter diameter spherical universe **700**. This sphere was divided equally into two parts: a low-density atmosphere **710** and ground **100**. The ground **100** simulated soil having a mixture of SiO_2 (70%) and void space (30%). The SiO_2 was taken to have a specific gravity of 2.20; the void space can be filled with varying fractions of water, representing soil with varying degrees of saturation. The source **50** was located 1 cm above the surface of the geometric center of the sphere. The detector **60**, representing a 0.4053 megaPascal ^3He detector, was in the form of a 2.5-cm thick, 15-cm diameter cylinder and was located with its lower surface 1.5 cm above the soil. The neutron shield **70** was a 1-cm thick boron layer of unit density and surrounded the top and sides of the detector **60**. The target **110**, intended to represent a mine, was a 100-g, 5.75-cm diameter, 2.5-cm thick piece of material with the chemical composition $C_3H_6N_6O_6$, intended to represent RDX, a commonly used explosive. This series of experiments was intended to represent a very difficult-to-detect target.

These computer experiments consisted of following the history of 5,000,000 neutrons, a number found sufficient to give statistically meaningful results, emitted with a ^{252}Cf spectrum, recording the time interval during which an interaction occurred in the detector for two cases: the target absent and the target present. The times that were studied covered a very wide range beginning with the emission of the neutron with 10-ns time bins for short times, increasing to 100 ns, then to 250 ns, and so on. This permits assessing the performance of the detector system for a wide variety of time delays and window sizes. These experiments were conducted for a variety of conditions: 1) soil moisture saturation of 0%, 10%, and 25% with the target at 1 and 2.5 cm below the surface and 2) target located 1, 2.5, 5.0, 7.5, 10.0, 12.5, 15.0, and 17.5 cm below the surface with 0% soil moisture saturation.

The data from the computer experiments were analyzed to determine: 1) the optimum time delay starting to count events and 2) the optimum window size to count. For the purpose of determining the optimum time delay, a total number of test neutrons of 367,000 was chosen; this number of neutrons provided a direct comparison with a one-second measurement with the equipment used in Example 1. For the analysis, the cumulative counts by the detector were determined as a function of the time delay in collecting counts without the target and with the target at various depths in the soil. From these, the detection efficiency was calculated for each time delay and compared to that with no time delay. The ratio of the detection efficiency with the time delay to that with no time delay is referred to as the improvement.

FIG. 7c shows the detection efficiency as a function of the time delay after the neutron emission for various target depths and for dry soil; **FIG. 7d** shows the relative improvement in detection efficiency, compared to the case in which there is no time delay for various target depths and for dry soil. The time delay for which detection efficiency is maximum varies in the range of 50 to 100 ns with target depth and the improvement in detection efficiency is on the order of a factor of 2, consistent with the laboratory experiment described in Example 1.

Similarly, **FIGs. 7e-f**show the detection efficiency and relative improvement in detection efficiency, respectively, compared to the case in which there is no time delay for 1-cm target depths and 0%-, 10%-, and 25%-saturated soil. **FIGs. 7g-h** show the detection efficiency and relative improvement in detection efficiency, respectively, compared to the case in which there is no time delay for 2.5-cm target depths and 0%-, 10%-, and 25%-saturated soil. These data show, similar to those in **FIGs. 7c-d**, that time delays of 20 to 70 ns are optimal and the drier the soil and the shallower the target are, the shorter the optimal time delay. This means that, in operation for detection of targets, the time delay may be chosen specifically to match the degree of soil saturation and

expected target depths or set at a single value of order 100 ns or less leading to slightly sub-optimal detection efficiency for some conditions.

For purposes of assessing the effect of varying the window size after the time delay, a time delay of 100 ns was chosen. The efficiency was calculated for various window sizes after after this time delay. This is compared with the efficiency obtained with the same time delay but with no window. The ratio of the windowed efficiency to the efficiency without a window is referred to as the improvement. The efficiency and improvements are shown in **FIGs. 7i-j**, as a function of window size for a 100-g disc of RDX 1 cm below the surface and in **FIGs. 7k-l** for 2.5 cm below the surface. **FIGs. 7m-n** show the efficiency and improvements for dry soil with the target at various depths below the surface.

These data show that for shallow targets, a window size of 20 μsec to 40 μsec (20,000 ns to 40,000 ns) provides a maximum in detection efficiency and improvements over detection efficiency in the absence of a window. Furthermore, when the target becomes more difficult to detect, whether because the target is deeper or because the soil contains more moisture, larger window sizes provide greater detection efficiency and improvements in efficiency.

CLOSURE

While embodiments of the present invention have been shown and described, it will be apparent to those skilled in the art that many changes and modifications may be made without departing from the invention in its broader aspects. The appended claims are therefore intended to cover all such changes and modifications as fall within the true spirit and scope of the invention.